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Friends or foes? Population dynamics of beneficial and detrimental aerial arthropods under Conservation Agriculture

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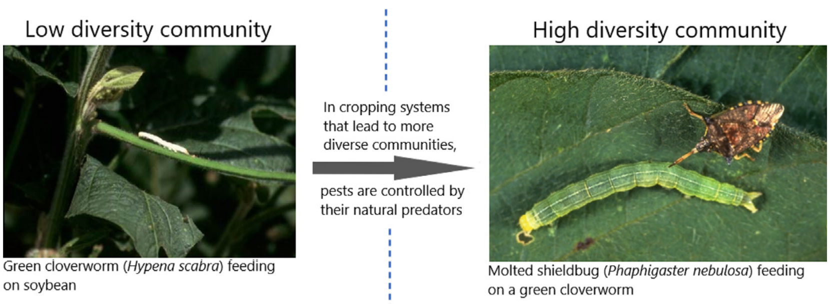
GRAPHICAL ABSTRACT



Green cloverworm (*Hypena scabra*) feeding on soybean

Molted shieldbug (*Phaphigaster nebulosa*) feeding on a green cloverworm

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ABSTRACT

Arthropod pest control is one of the most critical agronomic practices in cereal-based cropping systems. Cropping systems that preserve or promote biological pest control agents are more desirable. Data collected from a long-term trial at the Monze Farmer Training Centre (MFTC) from 2009 to 2012 was used to compare effects of different Conservation Agriculture (CA) systems with conventional practices (CP) on arthropod species diversity and populations with specific emphasis on beneficial and detrimental aerial arthropods. Up to 13 arthropod orders comprising of 40 species were identified in the cropping systems and their population density differed in years and cropping systems. Higher diversity was observed in CA systems in all years based on the Shannon-Weiner indices ranging from 0.4 to 2. However, a CP system with no rotations (CP-M) showed comparable results in the year with low rainfall. Community evenness increased in the same year with a value of 0.46. More beneficial and detrimental arthropods were recorded in a CA system with a three-year rotation of maize, cotton and sunnhemp reaching up to 9533 individuals ha^{-1}. The CP-M recorded the highest increase in detrimental arthropods from 2009 to 2012. A canonical correspondence analysis did not show a clear-cut association of both CA and CP systems with either beneficial or detrimental arthropods. However, associations were more driven by seasonal effects. Reduced soil disturbance, crop residue retention and crop diversity in CA systems preferentially attracted beneficial arthropods while preserving existing favourable arthropods. Conventional tillage systems

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often disturbed arthropod habitats, disrupted their life cycles leading to lower biological activity. Increased biodiversity from CA systems may therefore support biological control.

1. Introduction

Insect pests are among the major constraints to crop production in sub-Saharan Africa (SSA) (Odendo et al., 2003). For instance, yield losses of up to 58% in maize (*Zea mays* L.) due to fall army worm (*Spodoptera frugiperda*) alone have been reported in Zimbabwe (Chimweta et al., 2019). However, the level of yield loss depends on the extent of infestation (Baudron et al., 2019) and yield losses of up to 73% have been reported when there is 100% infestation of the crop (Hruska and Gould, 1997). Arthropod pests compete with humans and livestock for crops which are used as food and feed, respectively (Muthaiyan, 2009). Arthropod pests are often regarded as detrimental to agricultural production and livelihoods and can reach epidemic levels in some years (Wild, 2017; Wood and Cowie, 1988).

The productivity of some of the world's major crops such as maize and cotton largely depends on successful field pest management. Both crops are attacked by several pests such as stalk borer, pink bollworm, and cut worms from early seedling stages to maturity (Pearson, 1958; Walker, 1983). Thus, there is need for effective monitoring and management of crop pests in order to keep their populations below economic thresholds. In cotton production systems, crop residues are usually burnt to avoid the carry-over of diseases and pests into the next season.

Often, successful arthropod pest control is achieved by using chemical control methods (Aktar et al., 2009). However, most smallholder farmers are resource constrained and purchasing of expensive chemicals may be out of their reach (Foti and Chikuvire, 2005; Ngowi et al., 2007). Moreover, in areas with low literacy levels, smallholder farmers may find it difficult to follow the instructions on the chemical labels and end up using the chemicals erroneously thus reducing their efficacy or expose the users and the environment to hazards and risks (Ajayi et al., 2011). When correctly used, pesticides are efficient. However, they also harm non-targeted beneficial arthropod species (such as the lady beetles (*Coccinella magnifica*) that feed mainly on aphids). Reductions in beneficial arthropods negatively affect biological control system which is inherently one of the key benefits of more diversified systems (Geiger et al., 2010).

When farmers manage to apply pesticides, proper timing of application is a requirement as their efficacy is affected by factors such as weather conditions and mode of action. For example, spraying of contact pesticides shortly prior to rains may lead to the pesticide being washed away before being effective hence uneconomical (Wu et al., 2007). Emerging insect resistances to different products has been a downside of chemical arthropod pest control e.g. Kranthi et al. (2002) reported pink bollworm (*Pectinophora gossypiella* (Saunders)) resistance to pyrethroids while Guedes et al. (2019) reported pesticide resistance by the tomato pinworm (*Tuta absoluta*).

Integrated pest management (IPM) is a more economical, efficient and environmentally-benign way of controlling arthropod pests (Ehler, 2006). Integrated pest management refers to the use of one or more pest management strategies that are in the socioeconomic context of farming systems, the associated environment and population dynamics of the pest species to keep arthropod pests below an economic threshold (Dent, 1995). Under IPM there are cultural (e.g. timing of planting or crop spacing), biological (using natural enemies i.e. predators, parasites, pathogens and competitors or bio-pesticides), chemical (e.g. pesticides) and mechanical (e.g. hand picking of insects) methods of pest control which may be used simultaneously depending on the targeted pest (Bottrell, 1981).

Biological control is an important aspect of IPM which has been advocated for by many researchers (e.g. Hoodle and Van Driesche, 1998). A great shift from the use of pesticides to biological pest control is being noted in European farming systems (especially in horticultural systems) where predatory or parasitic fauna provide a more environmentally-friendly method of pest control compared to using chemicals (Geiger et al., 2010; Urbaneja-Bernat et al., 2019). Biological control is more specific and has no risk of development of arthropod resistance and reduces harm on untargeted species although its success depends mainly on protection of the natural enemies (Rusch et al., 2010). Natural predators of the arthropod pests kill and feed on the pest leading to a decrease in number, thus reducing the pest over time (DeBach and Rosen, 1991).

Agricultural practices may result in shifts in the diversity and populations of aerial arthropods that are either beneficial or detrimental to overall crop production (Harrison et al., 2019). Cultivation and burning of crop residues which are common in conventional crop production systems, have been used as means of breaking arthropod pest life cycles with tremendous effects to the environment. This will affect all arthropod groups including the beneficial species. Crop rotations, another biological pest management strategy, has been widely used in an effort to take away the host plants of pest which leads to their control (Thierfelder et al., 2014). However, rotations need to be strategically planned to avoid providing alternative host plants to the pests. There is need for the conservation of natural enemies (beneficial arthropods) to maintain their biodiversity and populations in cropping systems.

Conservation Agriculture (CA), which is defined by minimum soil disturbance, retention of crop residues (instead of burning) and diversification (e.g. crop rotations or intercropping) (FAO, 2012) has been reported to be a crop production system that maintains macrofaunal diversity while improving crop yields (Mashavakure et al., 2019a,b). Due to minimum soil disturbance under CA (i.e. no inversion tillage), arthropod habitats are less disturbed and micro-environments that favour their proliferation are created. In addition, more diversified systems (e.g. with crop residues, intercrops and/or trees and shrubs) lead to increased niche differentiation and also provide shelter and hunting ground for predators (Mashavakure et al., 2019b). Increased biological activity in CA systems, however, may promote the occurrence of undesirable pest species but also predominance of their natural enemies (Ketipearachchi, 2005). In their study, Rabary et al. (2011) reported increased white grubs under no-till systems but also their increased biological control due to promotion of their natural enemies.

Positive and negative shifts in incidences of pest and disease attack, damage and effects on crop yields have been reported under CA in the Indo-Gangetic plain (Jaipal et al., 2002). Hobbs et al. (2008) and others found an increase in beneficial fauna in south Asia such as large and predatory beetles, spiders, ants, wasps and earwigs (Jaipal et al., 2002; Kendall et al., 1995). Mashavakure et al. (2019a,b) found abundant increase in hunting spiders and soil dwelling beetles in CA systems of Zimbabwe. Ground cover was the main environmental enabler besides no-tillage which increased ants, spiders and beetles to help controlling detrimental fauna such as aphids, thrips, bollworms and grasshoppers (Stewart et al., 2003).

Literature on the effects of CA practices on the diversity and populations of aerial beneficial and detrimental arthropods is limited. The present study seeks to test the following hypotheses: a) CA cropping systems lead to an increase in number of beneficial arthropods in maize-cotton systems b) CA enhances biological activity and associated biological control. An understanding of the impact of CA systems on biological activity of aerial arthropods is important in designing

ecologically-based IPM programmes particularly in the SSA region

2. Materials and methods

The experiment was conducted in a CA long-term trial, that assessed the long-term effects of CA on soil quality. It was established at Monze Farmer Training Centre (MFTC) (Latitude 16.241, Longitude 27.442 and 1109 m above sea level.) from the 2005/2006 growing season and the current study was carried out from 2008/2009 to 2011/2012 cropping seasons. Data from the 2009/2010 cropping season was not captured. Monze Farmer Training Centre is situated in the Kafue river basin of southern Zambia and soils are classified as *Lixisols* (WRB, 1998). The site receives a long-term average annual rainfall of 748 mm (from November to April in a normal season) and experiences average daily temperatures of 22.2 °C. The site has been described at length in previous publications, see for example Thierfelder and Wall (2010, 2009).

2.1. Description of experiment, treatments and management

The experiment was set up in a randomised complete block design (RCBD) with initially eight treatments (called “cropping systems” where necessary) replicated in four blocks. However, the present study investigated only six of the treatments to assess their effects on arthropod populations (Table 1). These six treatments were:

i. Conventional farmer’s practice with maize sown as a monocrop in all years (CP-M)
ii. Conventional tillage with a maize-cotton (*Gossypium hirsutum* L.) two-year rotation (CP-MC): The rotation started with maize and then followed by cotton and the sequence was repeated over the years.
iii. Conventional tillage with cotton-maize two-year rotation (CP-CM): The rotation started with cotton and then followed by maize and the sequence was repeated over the years.
iv. Conservation Agriculture with a maize-cotton two-year rotation (CA-MC). The rotation started with maize and then followed by cotton and the sequence was repeated over the years.
v. Conservation Agriculture with cotton-maize two-year rotation (CA-CM). The rotation started with cotton and then followed by maize and the sequence was repeated over the years.
vi. Conservation Agriculture in maize-cotton-sunnhemp (*Crotalaria juncea* L.) three-year rotation (CA-MCS). The rotation started with maize, followed by cotton and then sunnhemp and the sequence was repeated over the years.

For the CP-based systems, tillage was done using an animal-drawn mouldboard plough at a depth of 10–15 cm and all crop residues were removed from the plots after harvesting. For the CA-based systems, sowing of both crops was done using a single row animal-drawn direct seeder from Fitarelli® and crop residues were retained on the soil surface at a rate of 2.5–3 t ha^{-1}, dry-weight basis.

The plots measured 300 m^2 (10 m × 30 m). In all years, maize was sown at a target population of 44,000 plants ha^{-1} (90 cm × 25 cm row spacing) and fertilized with 107 kg N: 33 kg P_2O_5: 17 kg K_2O ha^{-1} according to local recommendations. Cotton was planted at a target population of 44,444 plants ha^{-1} (90 cm × 50 cm with 2 seeds per station) and was fertilized at the same rate as the maize crop. Sunnhemp seed was dribbled into rip lines spaced at 0.45 m at a rate of 40 kg seed ha^{-1} to achieve a plant population of 444,000 plants ha^{-1}. Glyphosate [*N*-(phosphono-methyl) glycine] was applied as an initial non-selective post-emergence herbicide at planting at the rate of 1.205 L ha^{-1} active ingredient followed by hand hoe weeding whenever necessary. The trial site was fenced to preserve previous crop residues *in-situ* to be able to quantify their benefits in the long term. The cotton crop was uprooted, and the residues retained in the same CA treatment plots instead of burning them as encouraged by local extension services to prevent pest and disease carry-over into following years.

2.2. Aerial arthropod sampling

The arthropods were frequently scouted twice a week in all plots using standard scouting procedures, recommended by the Zambian extension services. Arthropods were sampled in all plots using different methods at least twice during the season i.e. in cotton at first flowering stage and first boll stage and at the same time in the maize and sunnhemp plots. For flying arthropods, catching nets were used while for the other crawling ones, *in-situ* counting was done in the whole plot (McGavin, 2007). Collected arthropods were preserved in flasks with alcohol and classified at species level in the laboratories at Mt Makulu Research Station in Zambia by an entomologist according to standard classifications, protocols and procedures. The populations of each species in each treatment were recorded at each sampling occasion.

2.3. Data management and statistical analyses

Arthropods were put into guilds based on their order before determining their abundance. Arthropod relative abundance was determined for each guild in each cropping system separately for each year. Relative abundance was calculated as the proportion of the guild population in relation to the total population of all collected guilds across all cropping systems and replicates in each year and expressed as a percentage. The effects of cropping systems and species and their interaction on abundance were analyzed using mixed models (see below). Cropping systems and species were included as fixed effects. Blocks and plots within blocks were included as random effects, to account for grouping factors and repeated measures across years in the same plots. Variance components were estimated by using maximum likelihood estimation in the 'Asreml-R' as well as using 'lme4′ packages (Bates et al., 2015; Butler et al., 2009) in R environment (R Core Team, 2019). The significance of fixed effects was tested by using Wald chi-square tests. Where the F-test was significant between treatments, years and the interaction, separation was done using multiple comparison procedure with multiplicity adjustment at least significance difference (LSD) of 5% probability level (Bretz et al., 2016), as implemented in the 'emmeans' package (Lenth, 2019). The codes used for analysis in R software are given in the Supplementary Material (Code S1).

Arthropod species community diversity (hereafter referred to as diversity where necessary) was calculated using the Shannon-Weiner

Table 1
Crops that were grown in each treatment in each season from 2005 to 2012 at Monze Farmer Training Centre.

Treatments	2005/06	2006/07	2007/08	2008/09	2009/10	2010/11	2011/12
CP-M	Maize	Maize	Maize	Maize	Maize	Maize	Maize
CP-MC		Maize	Cotton	Maize	Cotton	Maize	Cotton
CP-CM		Cotton	Maize	Cotton	Maize	Cotton	Maize
CA-MC	Maize	Cotton	Maize	Cotton	Maize	Cotton	Maize
CA-CM	Cotton	Maize	Cotton	Maize	Cotton	Maize	Cotton
CA-MCS	Maize	Cotton	Sunnhemp	Maize	Cotton	Sunnhemp	Maize

diversity using the *diversity()* function in the 'vegan' package (Oksanen et al., 2019) in R environment. Arthropod species community richness (hereafter referred to as richness where necessary), that is the number of species per plot was determined using the *specaccum()* function in the 'vegan' package. The calculations for diversity and evenness (hereafter referred to as evenness where necessary) indices were based on the following equations: Shannon-Weiner diversity index (H') [Eq. (1)], and evenness (E') index [Eq. (2)] (Shannon and Weiner, 1963):

$$H' = N\ln N - \frac{\sum (n\ln n)}{N} \tag{1}$$

$$E' = \frac{H'}{\ln N} \tag{2}$$

where:

H' is the species diversity through proportional number of species. Higher values of H' signify a greater diversity. N is the total population density per plot and n is the species population of each species found within this location. E' is the relationship between the observed number of species and the total number of species. Greater values of E' mean greater uniformity between species abundances. Species richness is the number of different faunal species observed per plot. The codes used for analysis in R software are given in the Supplementary Material (Code S2).

The effects of years and cropping systems and their interaction on species diversity, species evenness, and species richness were analysed using mixed models as described for previous models in Code S2. The codes used for the analyses in R software are given in the Supplementary Materials (Codes S3). The present species were further categorised as either beneficial or detrimental depending on their nature and characteristics of association with the crops and were analysed using the same models (Codes S3).

Graphical analysis of the residuals was used to assess the homoscedasticity and normality of observations in the data and where skewness range was too wide (indicating high variability), the data was log (x + 1) transformed. Canonical correspondence analysis (CCA) (ter Braak, 1986), was performed to assess the ordination of arthropod species, cropping systems (explanatory variables) and years (covariables) to better explain their relationship. The choice of the ordination method used was based on prior analysis of the data using detrended correspondence analysis (DCA) which assessed the length of the longest gradient axes based on the Hill's scaling of ordination scores (Hill and Gauch, 1980). The length of the longest gradient was 4.3 standard deviations (SD) indicating high deviation of the data from the assumed linear response thus more appropriate to carry out a unimodal model

Table 2
Species that were identified in each treatment and in each season in the 2009, 2011 and 2012 seasons.

Category[a]	Species		2009 Treatment[b]						2011						2012					
	Common name	Scientific name	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
Detrimental (Be)	American bollworm	*Helicoverpa armigera*	–	–	–	–	–	–	–	–	–	+	–	–	–	–	–	+	–	+
Detrimental (Ss)	Aphids (maize)	*Rhopalosiphum maidis*	+	+	–	–	+	+	+	–	–	–	+	–	+	–	–	+	–	+
Detrimental (Ss)	Aphids (cotton)	*Aphis gossypii*	–	–	+	+	–	–	–	–	+	+	–	–	–	+	–	–	+	–
Detrimental (Le)	Black beetle	*Epicauta pennsylvanica*	+	–	–	+	+	+	–	+	+	+	+	+	+	+	+	+	+	+
Detrimental (Le)	Caterpillar	–	+	–	+	–	+	+	–	–	–	+	–	+	+	+	+	+	+	+
Detrimental (Fe)	Blister beetle	*Actenodia* spp.	–	+	–	+	+	–	–	–	–	–	–	+	+	+	–	–	+	–
Detrimental (Be)	Cotton bollworm	*Helicoverpa armigera*	+	–	–	–	+	–	–	–	–	–	–	–	–	–	–	–	–	–
Detrimental (Be)	Cotton stainer	*Dysdercus suturellus*	–	–	+	+	–	+	–	–	+	+	–	–	+	+	–	–	+	–
Detrimental (Le)	Field cricket	*Gryllus assimilis*	–	+	–	–	+	–	–	–	–	–	–	–	–	–	–	+	+	–
Detrimental (Le)	Elegant grasshopper	*Zonocerus elegans*	+	–	+	+	+	+	–	–	+	+	+	–	–	+	+	–	–	–
Detrimental (Fe)	Fruit fly	*Drosophila melanogaster*	–	–	–	+	–	+	–	–	–	–	–	–	–	–	–	+	–	+
Detrimental (Le)	Grass hopper	*Schistocerca gregaria*	–	–	+	+	–	+	–	–	+	+	–	–	+	+	+	+	+	+
Detrimental (V)	Jassids (maize leaf hopper)	*Cicadulina bimaculata*	–	–	–	–	–	+	–	–	–	–	+	–	+	–	+	+	–	+
Detrimental (V)	Jassids (cotton leaf hopper)	*Amrasca terraereginae*	–	–	–	+	–	–	–	–	–	+	–	–	–	+	–	–	+	–
Detrimental (Le)	Leaf beetle	*Oulema melanopus*	–	–	–	–	–	+	–	–	–	–	–	–	–	–	–	–	–	–
Detrimental (Le)	Cotton serpentine leaf miner	*Liriomyza trifolii*	–	–	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Detrimental (Fe)	Maize silk worm	*Helicoverpa zea*	+	–	–	–	+	–	–	–	–	–	–	–	–	–	–	–	–	–
Detrimental (Be)	Pink bollworm	*Pectinophora gossypiella*	–	–	+	+	–	–	–	–	–	+	–	–	–	+	+	–	+	+
Detrimental (Lv)	Pyralidae spp (Moths)	*Pyralidae* spp.	–	–	–	–	–	+	–	–	–	–	–	–	–	–	–	–	–	–
Detrimental (Se)	Semi looper	*Chrysodeixis eriosoma*	–	–	+	+	+	–	–	–	–	–	–	–	–	–	–	–	–	–
Detrimental (Lv)	Grain moth	*Sitotroga cerealella*	–	–	–	–	–	+	–	–	–	–	–	–	–	–	–	–	–	–
Detrimental (Se)	Maize stalk borers	*Papaipema nebris*	–	+	–	–	–	–	–	–	–	–	–	–	+	–	–	–	–	–
Detrimental (Fe)	Sawflies	*Tenthredo mesomela*	–	–	–	–	–	+	–	–	–	–	–	–	–	–	–	–	–	–
Detrimental (Ss)	Stink bug	*Halyomorpha halys*	+	–	–	–	+	–	–	–	+	+	+	–	–	+	+	–	+	–
Detrimental (Fe)	Thrips	*Ponticulothrips diospyrosi*	+	+	+	–	–	+	–	–	–	–	–	–	–	–	–	–	–	–
Detrimental (Ge)	Weevils	*Sitophilus zeamais*	–	–	–	–	+	+	–	–	–	–	–	–	–	–	–	–	–	–
Beneficial (Pr)	Ants	*Pachycondyla verenae*	+	+	+	+	+	+	–	–	–	–	–	–	–	–	–	–	–	–
Beneficial (P)	Bees	*Apis mellifera*		–	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Beneficial (Pr)	Brown ant	*Monomorium pharaonis*	+	+	–	+	+	–	–	–	–	–	–	–	–	–	–	–	–	–
Beneficial (P)	Butter fly	*Papilio machaon*	–	–	–	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Beneficial (Ss)	Mosquito bugs	*Helopeltis schoutedeni*	–	–	–	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Beneficial (Pr)	Hover flies	*Eupeodes corollae*	–	–	+	–	+	+	–	–	+	+	+	+	+	+	+	+	+	+
Beneficial (Pr)	Lace wing	*Chrysoperla carnea*	–	–	–	–	–	+	–	–	–	–	–	–	–	–	–	–	–	–
Beneficial (Pr)	Lady bird	*Coccinella septempunctata*	+	–	+	+	–	–	–	–	–	–	+	–	–	+	–	–	–	+
Beneficial (Pr)	Praying mantis	*Tenodera sinensis*	–	–	–	–	–	–	+	–	–	+	+	–	+	–	–	+	+	+
Beneficial (Pr)	Spiders	*Araneae* spp.	+	+	–	+	+	+	+	–	+	+	+	+	+	+	+	+	+	+
Beneficial (D)	Termites	*Coptotermes formosanus*	–	–	–	+	–	–	–	–	–	–	+	–	+	–	–	–	–	+
Beneficial (P)(Pr)	Wasps	*Ropalidia marginata*	–	–	–	+	–	+	–	+	+	+	+	+	+	+	+	+	+	+

[a] The letters in parentheses represent arthropod beneficial and detrimental class: Be = boll eaters; Pr = predators, Ss = sap suckers, P = pollinators, Le = leaf eaters, V = disease vectors, D = decomposers, Ge = grain eaters, Fe = flesh eaters.

[b] Treatment are represented by numbers as follows: 1 = CP-M; 2 = CP-MC; 3 = CP-CM; 4 = CA-MC; 5 = CA-CM and 6 = CA-MCS. "+" means that species was present while "-" signify absence of faunal species within the respective treatments and season.

based ordination (Ter Braak and Šmilauer, 2002). Rare species were down-weighted during the analysis. Unrestricted Monte Carlo permutational tests were done (set at 999 permutations) to allow the determination of statistical significance of the relationship between the cropping systems, years and species. All data analysis and visualisation for this section was done using CANOCO version 5.11 (Lepš and Šmilauer, 2014). However, for the other sections, graphical artwork was done using 'ggplot2' function (Wickham, 2016) in R software.

3. Results

3.1. Rainfall distribution throughout the years

Rainfall regimes varied throughout the different cropping seasons (Fig. S1, Supplementary material). The least rainfall was received in 2012 with a cumulative total of 628 mm as compared to other years. The greatest amount of rainfall was received in 2009 (mean of 843 mm). Rainfall distribution was fairly even in all years, but long dry spells were recorded in all years. However, cumulative rainfall variation between the years was 10.9%.

3.2. Arthropod species characteristics and abundance in different cropping systems and years

In this current study, 38 species were identified from the six different cropping systems combined for all years (Table 2). The identified species were grouped into beneficial and detrimental guilds (based on their orders) based on their effects to crops in their current stage as well as consecutive stages. In total, 13 guilds of the arthropods were identified across all years (Fig. 1). These arthropod groups consisted of 12 beneficial species and 26 detrimental ones (Table 2, Fig. 1).

The beneficial arthropods group were classified into pollinators (e.g. bees, wasps), predators of detrimental arthropods (e.g. ladybird, wasps, praying mantis and spiders), and decomposers (e.g. termites). The detrimental arthropods group could be classified as sap suckers (e.g. aphids), leaf eaters (e.g. elegant grasshoppers, blister beetle, leaf miner and leaf beetles), stem/stalk borers (e.g. maize stalk borer and semi-looper), parasitoids (e.g. jassids and mosquito bugs), and herbivorous grain/boll eaters (e.g. weevils, American bollworm, pink bollworm, and cotton bollworm) (Table 2). For example, the cotton stainer (*Dysdercus suturellus*) appeared in treatments CP-CM and CA-MC during the 2009 and 2011 years and in treatments CP-MC and CA-CM in the 2012 year (Table 2). However, the cotton stainer also appeared during the years when cotton was not planted although it was in a few cases e.g. in the CA-MCS treatment in the 2009 year. The appearance of some arthropod groups was year-specific e.g. grasshoppers (*Schistocerca gregaria*) which appeared in the driest year 2012 in all treatments (Table 2).

Arthropod abundance differed significantly based on the order in 2009 (Wald χ^2 = 70.3, d.f. = 13, $p < 0.001$) and 2012 (Wald χ^2 = 31.8, d.f. = 8, $p < 0.001$) (Table 3). The abundance of arthropod guilds differed significantly in different cropping systems in 2011 (Wald χ^2 = 190.5, d.f. = 45, $p < 0.001$). Among the dominant guilds, the *Hymenoptera* was most abundant across all cropping systems in 2009 contributing up to 70% of the total abundance (Fig. 2a). The *Hymenoptera* was the most abundant guild in 2011 contributing 66% and 57% of the total abundance in the CP-M and CA-MCS cropping systems, respectively (Fig. 2b). *Hymenoptera* was an important guild that appeared in fairly high relative abundances across all cropping systems in

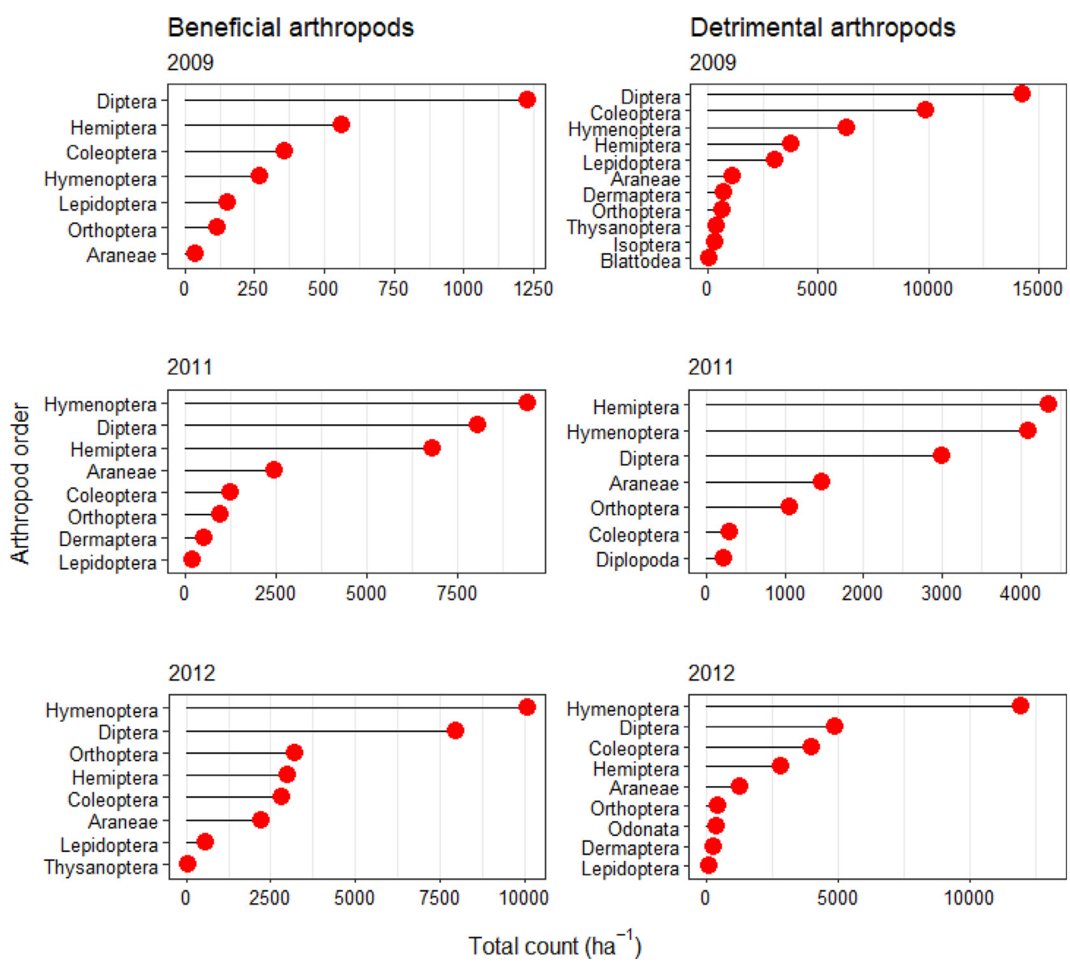

Fig. 1. Guilds of beneficial and detrimental arthropods grouped by their order observed across all plots in 2009, 2011 and 2012.

Table 3
Linear mixed model output (combined model) explaining the effects of species group, cropping systems and their interaction on abundance of guilds of arthropods in different years.

	Source	Degrees of freedom	Sum of Squares	Wald Statistic	*P-value* [c]
2009	(Intercept)	1	984.7	18.157	2.0e−05 ***
	Group	13	3814.0	70.322	7.0e−10 ***
	System	5	0.2	0.004	1.0
	Group × System	65	1703.3	31.405	1.0
	Residual (MS)		54.2		
2011	(Intercept)	1	1741.5	58.34	2.2e−16***
	Group	9	5304.4	177.69	< 2.2e−16***
	System	5	0.0	0.0	1.0
	Group × System	45	5688.1	190.54	< 2.2e−16***
	Residual (MS)		29.9		
2012	(Intercept)	1	412.4	9.3	0.002**
	Group	8	1409.6	31.8	0.000***
	System	5	0.0	0.0	1.0
	Group × System	40	1369.6	30.9	0.8
	Residual (MS)		44.4		

[c]Asterisks and dots in front of numbers signify the level of significance where: 0 '***', 0.001 '**', '*', 0.05 '.', 0.1 ' ' 1.

2012 (Fig. 2c). Some guilds such as *Blattodea* and *Lepidoptera* appeared in low abundances in all cropping systems and in all years. In general, beneficial arthropods increased in numbers across the seasons, for example, the *Hymenoptera* increased by more than 20 times from 2009 to 2012. (Fig. 1). Other guilds such as the *Coleoptera* decreased in numbers over the years while other guilds such as the *Thysanoptera* consistently appeared in low numbers over the years (Fig. 1). Some guilds only appeared in some of the years and not in others e.g., *Diplopoda* and *Odonata* that appeared only in the 2011 and 2012 years respectively (Fig. 1).

3.3. Arthropod species diversity in different cropping systems and years

Arthropod species community diversity was affected by the interaction of years and cropping systems (Wald $\chi^2 = 56.3$, d.f. = 10, $p < 0.001$) (Table 4). The CA treatment that started with maize in a two-year rotation with cotton (CA-MC) consistently had the highest diversity of 2.00 in all the years (Fig. 3a). However, in 2009, the CP-CM treatment also showed high diversity which was the same as that of the CA-MC treatment (Fig. 3a). The conventional tillage treatments either with no rotation (CP-M) or with the two-year maize-cotton rotation (CP-MC) showed the least species diversity in the 2009 and 2011 years (Fig. 3a). In general, all treatments showed higher arthropod diversity

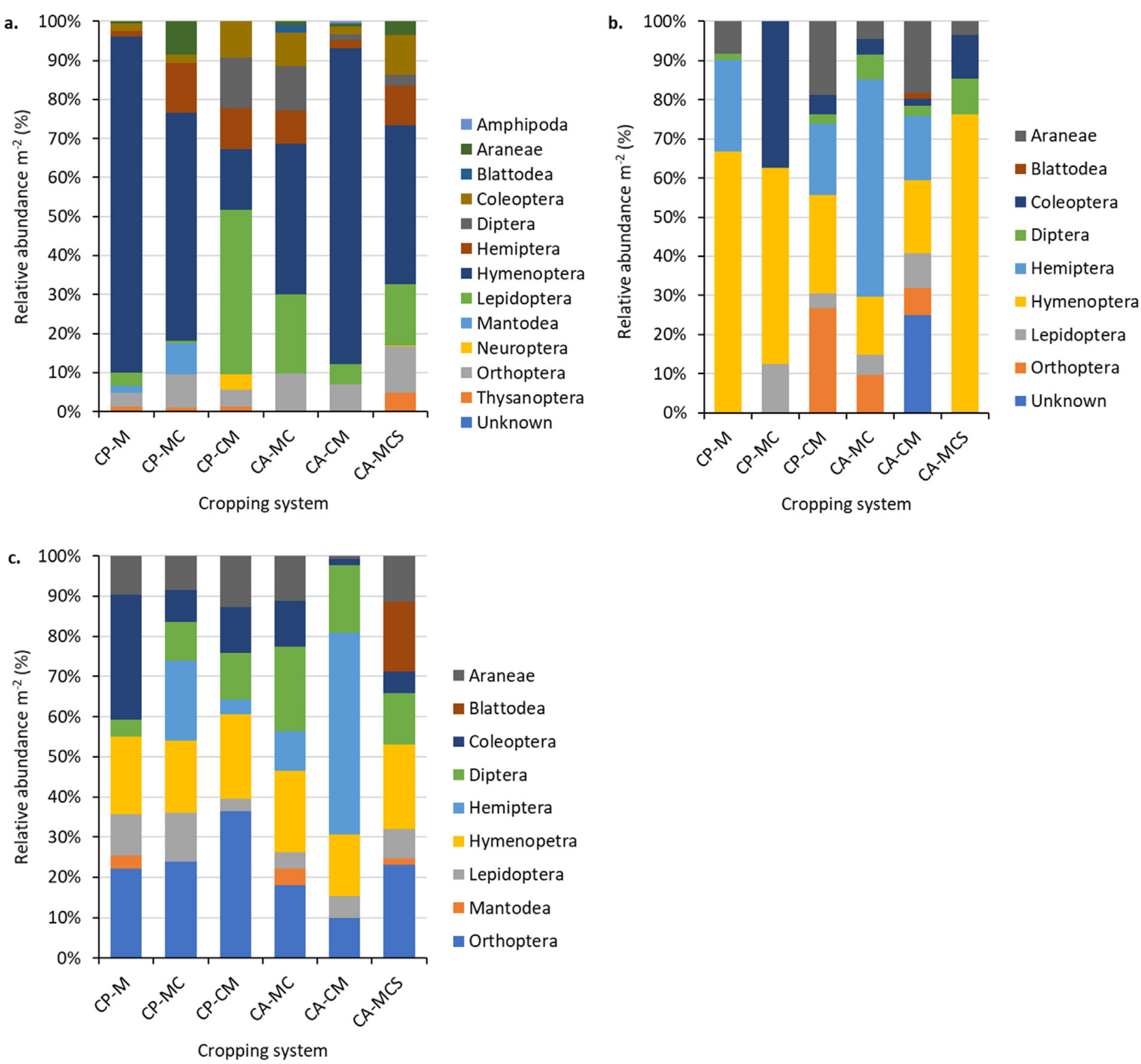

Fig. 2. Relative abundance (expressed in percentage) of different arthropod functional groups in all cropping systems in the years a) 2009, b) 2011 and c) 2012.

Table 4
Linear mixed model output (combined model) explaining the effects of different cropping systems (systems), years, and their interaction on species diversity, species evenness, species richness, density of beneficial arthropods and density of detrimental arthropods.

	Source	Degrees of freedom	Sum of Squares	Wald Statistic	*P-value* [d]
Diversity	(Intercept)	1	81.162	877.22	< 2e−16***
	Year	2	4.662	50.39	1.14e−11***
	System	5	9.224	99.7	< 2e−16***
	Year × System	10	5.209	56.3	1.80e−16***
	Residual (MS)		0.093		
Evenness	(Intercept)	1	9.593	289.292	< 2e−16***
	Year	2	0.3202	9.655	0.008006**
	System	5	0.2044	6.165	0.290495
	Year × System	10	0.2501	7.542	0.673501
	Residual (MS)		0.0332		
Richness	(Intercept)	1	1537.55	307.377	< 2e−16***
	Year	2	139.11	27.810	9.17e−07***
	System	5	224.94	44.969	1.47e−08***
	Year × System	10	200.72	40.127	1.61e−05***
	Residual (MS)		5.00		
Density of beneficial arthropods	(Intercept)	1	7.1e + 07	67.853	2.22e−16***
	Year	2	3.4e + 07	32.831	7.43e−08***
	System	5	2e + 07	18.772	0.00212**
	Year × System	10	3.8e + 07	36.125	8.01e−05***
	Residual (MS)		1,041,404		
Density of detrimental arthropods	(Intercept)	1	9,718,324	54.031	1.97e−13***
	Year	2	148,797	0.827	0.661246
	System	5	3,173,764	17.645	0.003426**
	Year × System	10	2,475,182	13.761	0.184166
	Residual (MS)		179,867		

[d]Asterisks and dots in front of numbers signify the level of significance where: 0 '***', 0.001 '**', '*', 0.05 '.', 0.1 ' ' 1

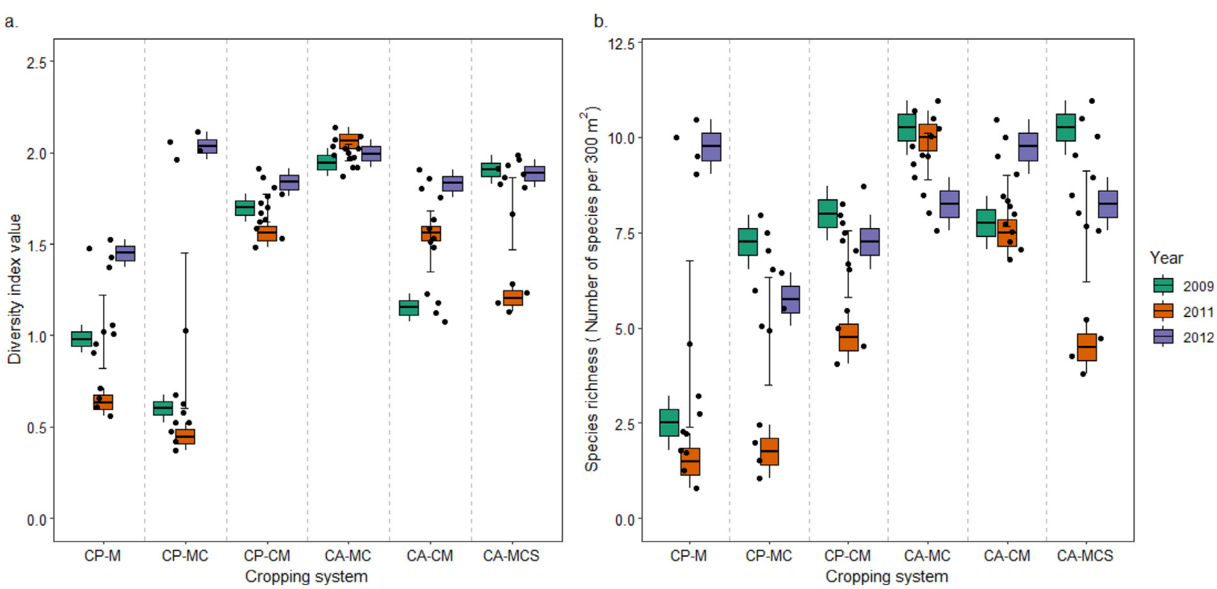

Fig. 3. Averages of best linear unbiased predictors fitted by restricted maximum likelihood showing the effects of different cropping systems and years on a) arthropod species diversity and b) arthropod species richness. The error bars represent the 95% confidence interval (CI) of the combinations of years and cropping systems (a 95% CI is ± 1.96 × standard error). The jittered points represent individual observations.

in the year 2012 (Fig. 3a).

Species richness was affected by the interaction of years and cropping systems (Wald $\chi^2 = 40.1$, d.f. = 10, $p < 0.001$) (Table 4). The CA treatment with the maize-cotton-sunnhemp rotation in 2009 together with CA-MC in 2009 and 2011, and CA-CM and CP-M in 2012 were the richest in species averaging 10 species per plot unit area (Fig. 2b). The CP treatments with no rotation and with a maize-cotton rotation in the year 2011 had the least species richness values averaging 1 species per plot unit area (Fig. 3b).

Significant differences in species community evenness were only observed between the years (Wald $\chi^2 = 9.7$, d.f. = 2, $p < 0.01$) (Table 4). Species communities were more even in the year 2012 with a mean evenness value of 0.46 compared to 2009 and 2011 (Fig. 4).

3.4. Beneficial and detrimental arthropods in different cropping systems and years

Beneficial arthropod populations were significantly affected by the interaction of cropping systems and years (Wald $\chi^2 = 36.1$, d.f. = 10, $p < 0.001$) while detrimental groups were only significantly affected by the different cropping systems (Wald $\chi^2 = 17.6$, d.f. = 5, $p < 0.01$) (Table 4). The density of beneficial arthropods was highest in 2009 with

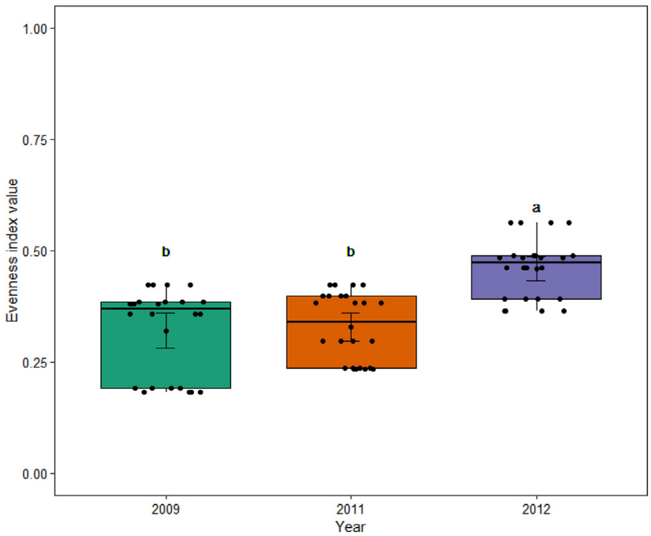

Fig. 4. Averages of best linear unbiased predictors showing the effects of different years on arthropod species evenness. The error bars represent the 95% confidence interval (CI) (a 95% CI is ± 1.96 × standard error). The jittered points represent individual observations.

a mean density of 1070 counts ha^{-1} as compared to that in 2011 and 2012 with means densities of 421 and 254 counts ha^{-1} respectively (Fig. 5a(i)–(iii)). The highest density of detrimental arthropods was also observed in 2009 as compared to other years. In all years, the density of beneficial fauna was more than that of detrimental faunae except for 2012 where detrimental faunae were 30% more (Fig. 5a(iii)). Conservation Agriculture-based systems CA-CM and CA-MCS had the highest number of beneficial arthropods of 1,012 fauna ha^{-1} and 773 fauna ha^{-1} across all years (Fig. 5b(i)). For the detrimental populations, the CA systems had the highest mean densities of 541 counts ha^{-1} in the CA-MCS system and 452 counts ha^{-1} in the CA-MC system across all the years respectively (Fig. 5b(ii)).

3.5. Association of different tillage systems and arthropod species in all years

The partial canonical correspondence analysis (CCA) showed an association among different faunal species, cropping systems and years (Fig. 6). The first axis (Axis 1) explained 42.7% (Eigenvalue = 0.19) of the cumulative fitted variation and distinguished a gradient of faunal species that were associated with CA-MCS (e.g. termites, *Sitotroga* spp and sawflies), CA-MC and CP-CM (e.g. cotton bollworm, semilooper, and cotton stainers) from those associated with CA-CM (e.g. brown ants and pink bollworm), CP-MC (e.g. American bollworm), CP-CM (pink bollworm), CP-M and CP-MC (e.g. caterpillars) (Fig. 6). The second axis explained 24.9% (Eigenvalue = 0.14) of the cumulative fitted variation and defined a gradient from faunal species that were associated with CA-MSC and CP-M to those associated with CA-MC, CP-CM and CA-CM. There was a clear 'stand-out' influence of the CA system with a three-year rotation (CA-MCS) on the faunae that are associated with it. These faunae included both beneficial and detrimental ones e.g., termites, sawflies and grain moths. As shown by the CCA output, both CA-based and CP-based cropping systems were associated with both beneficial faunae and detrimental faunae. The trend of association was not distinctively clear. However, the CCA output shows that most of the beneficial faunae were more associated with the year 2012 as compared to other years.

4. Discussion

4.1. Arthropod species characteristics and abundance in different cropping systems and years

The appearance of different arthropod species in cropping systems can be determined by availability of food (crops that are planted or prey species), shelter (for protection from natural enemies and for breeding), and environmental conditions (e.g. light, temperature, moisture) that

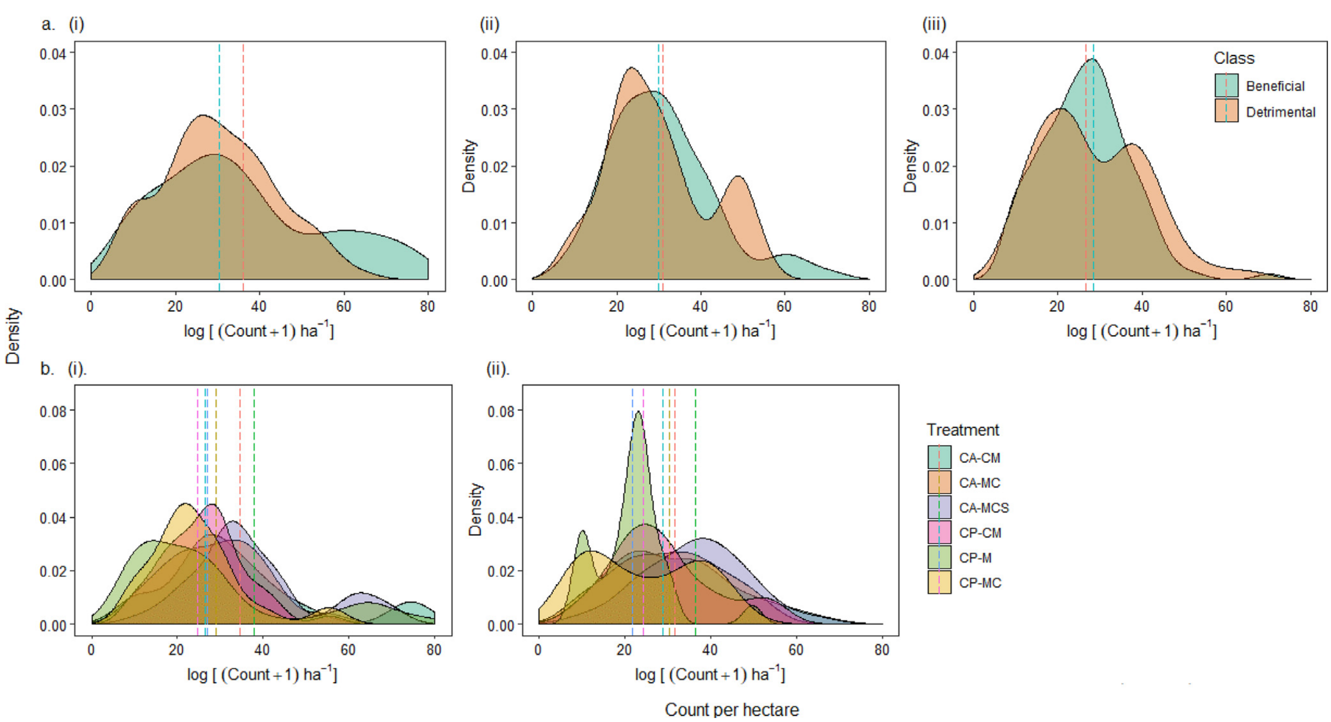

Fig. 5. (a) Density plots of years (i) 2009, (ii) 2011, and (iii) 2012 for beneficial and detrimental arthropod species log (x + 1)-transformed counts. (b) Density plots of years (i) beneficial and (ii) detrimental arthropod species for different cropping systems (treatments) log (x + 1)-transformed counts. The counts were expressed to per hectare basis.

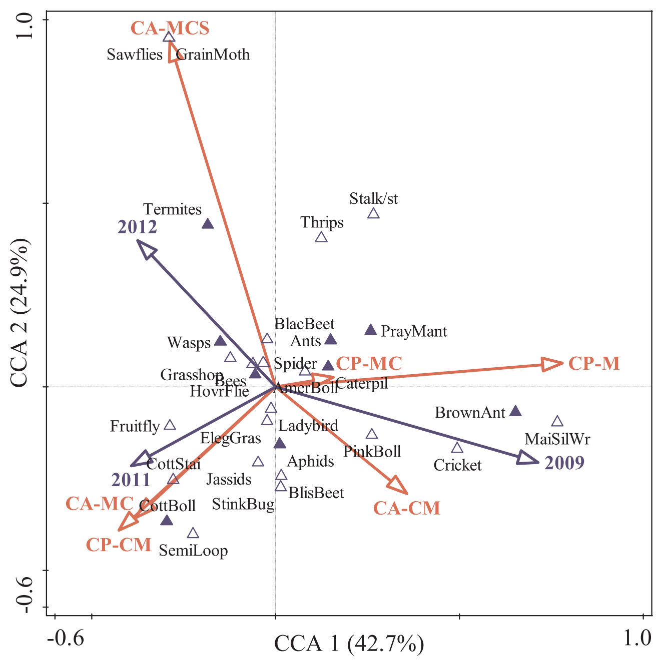

Fig. 6. Partial canonical correspondence analysis showing the projection of arthropod species data, years and management practices. Triplot with years, management practices and faunal species: grain moth (GrainMoth); sawflies; maize silkworms (MaiSilWr); maize stem/stem borers (Stalk/st); termites; thrips; blister beetles (BlisBeet); ants; wasps; black beetles (BlacBeet); American bollworms (AmerBoll); brown ants (BrownAnt); praying mantis (PrayMant); hoverflies (Hovrflie); caterpillars (Caterpil); grasshoppers (Grasshop); bees; spiders; pink bollworms (PinkBoll); lady birds; elegant grasshoppers (ElegGras); crickets; aphids; fruit flies (Fruitfly); jassids; cotton strainers (CottStai); stink bugs (StinkBug); semiloopers (SemiLoop); cotton bollworm (CottBoll). Rare species were down-weighted during the analysis. Detrimental arthropods are marked with empty triangles while beneficial arthropods are marked with filled triangles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

are found in the system (Wallner, 2003). Different crops attracted different species and in turn attracting different predators. For example, species that feed on cotton appeared mainly during the years when cotton was planted as well as in systems that involved cotton. However, some species were also observed in years when crops that are their main source of food or shelter were not planted e.g. the cotton stainer, and this may be due to the retention of the crop (cotton) residues on the soil instead of burning or removing them as per the traditional/standard extension directive. However, the populations of these detrimental species were regulated by the cropping system since it also promoted their natural enemies such as the spiders.

4.2. Arthropod species diversity in different cropping systems and years

The results of the present study showed that CA-based cropping systems had the highest arthropod diversity relative to CP systems. Reduced disturbance of the soil as well as diversification of plant associations in CA systems promoted the proliferation of various faunal species (Brainard et al., 2016). This resulted in highly diverse communities by not allowing the dominance of some species through natural predation (Sinclair et al., 2003). On the other hand, monocropping could have selectively increased the population of certain groups of arthropod pests particularly specialist herbivores resulting in the dominance of only such arthropods and a reduced diversity (Rämert et al., 2003). In this study, these arthropod species included the maize aphids (*Rhopalosiphum maidis*) and the black beetle (*Epicauta pennysylvanica*). This is evident in the very low species diversity index values observed in the CP-M treatment in which maize was planted continuously. Furthermore, the tillage-based systems with no residue retention had a negative effect on the recolonization of arthropods (Mutema et al., 2013) thus only promoted the success of a selected arthropod species that managed to proliferate in such conditions. This could also be the reason for reduced diversity that was observed in these systems.

As also observed by Mutema et al. (2013), reduced tillage systems with residue retention resulted in more species. Species richness in conventional tillage-based systems associated with monocropping was generally low and this may be attributed to increased soil disturbance and inversion which led to burial of certain life cycle stages of the arthropod species. The lack of surface residue cover in CP-based cropping systems also tend to inhibit habitation. Lack of crop rotations (monocropping) in such systems also promoted the success of a few species that depended mainly on maize leading to a reduced species richness. In their study, Stamps and Linit (1997) showed that crop polycultures resulted in increased arthropod diversity thus avoiding pest outbreaks.

Contrary to the old directive by the extension services of Zambia and some SSA countries that encourage the uprooting and burning of cotton residues to avoid build-up of pests and diseases (Chitah, 2016), cotton residues were retained on the soil surface in the CA systems in this study. No dramatic increases in arthropod pests were observed and this can be attributed to either increased biological activity and control which led to effective predation and due to the crop rotations, that regulated the populations of the arthropod cotton pests (Snyder, 2019).

4.3. Beneficial and detrimental arthropods in different cropping systems and years

In general, CA systems comprising of reduced tillage, plant residue retention and crop rotation led to more beneficial and detrimental arthropods when average across all seasons. The beneficial arthropods included natural predators of arthropod pests e.g. spiders and ladybird beetles and the detrimental arthropods included cotton bollworms and sawflies etc. The microenvironment created by these systems provided conducive habitats for a diverse arthropod population and within these populations were predators that fed on detrimental arthropods as well as common pests that fed on crops (Flint and Dreistadt, 1998; Johan, 2017).

Retention of crop residues created favourable conditions for the survival and breeding of predatory arthropods such as spiders and ladybird beetles thus encouraging their proliferation within such systems (Kladivko, 2001). Residues also promoted termite activity that in turn facilitated decomposition and soil organic matter build up. On the other hand, these residues also promoted proliferation of arthropods considered as common pests.

However, more detrimental fauna observed in the CP-MC system in 2012 year, respectively, was mainly due to the presence of cotton crops in that year. Naturally, cotton is susceptible to quite a number of arthropod pests and this resulted in more detrimental arthropods such as pink bollworm, aphids and American bollworm being the dominant species within the years cotton was grown (Boyd et al., 2004). The cotton plant has a peculiar way of attracting a variety of pests through exudation of nectar from its nectaries found under side of the leaves and on the outside of its squares on base of bract and leaflets (Amera et al., 2017; Ehler, 2006). This nectar attracts a variety of arthropods both beneficial and detrimental. In many cases, under natural conditions, the detrimental ones outnumber the beneficial ones making the use of the naturally occurring predators and parasitoids not an effective way of controlling pests in cotton hence the need for IPM (Amera et al., 2017; Ehler, 2006). However, rotation of cotton with maize resulted in a reduction of the populations of detrimental arthropods. These findings suggest that in CA, biological and cultural control as pest management tools can be enhanced using rotations.

4.4. Association of different tillage systems and faunal species in all years

In general, both CA and CP treatments were associated with both beneficial and detrimental arthropods. As shown by the CCA output as well as the diversity indices, the CA systems provided more balance for both beneficial and detrimental species. In CA systems, an eventual reduction in detrimental fauna due to crop rotations and predation by the predator arthropods is possible. These CA systems were more associated with both beneficial and detrimental arthropods as they provided more conducive microenvironments as compared to the tillage based systems hence leading to greater diversity in CA systems (Mutema et al., 2013).

However, the results of the present study suggest that crop rotations also negatively affected the populations of the beneficial arthropods which could thrive better under the presence of certain crops. Thus, rotations were capable of regulating the populations of arthropods in general and reduced the dominance of certain species (Brust and King, 1994). Yearly variability also played an important role on the resultant populations of both the beneficial and detrimental arthropods as abiotic factors play an important role in arthropod population dynamics (Eo et al., 2017).

Pests such as grasshoppers are usually prevalent during drier years (Maxmen, 2013) and this was also shown by their appearance in the year with low rainfall in all treatments of this current study. The guild *Blatodea* which was predominantly comprised of termites appeared only in the year with high rainfall and this may be attributed to their preference for high soil moisture and relative humidity (Zukowski and Su, 2017). However, a study by Mahesh (2015) could not establish a clear relationship between abiotic factors such as moisture, temperature and humidity with species populations. The relationship between species populations and abiotic factors may be masked by the presence of other species that are less likely to be affected by rainfall availability during the year. Karuppaiah and Sujayanad (2012) reported declines in species population with increasing temperatures as a result of climate change. However, the role of abiotic factors in regulating aerial arthropod communities in cropping systems was not quantified. Potentially, CA is one of the strategies that has potential to regulate arthropod populations by alleviating the detrimental effects of climate change (Rourke, 2017). The beneficial effect of rotation was also prevalent in CP systems with rotations which attracted beneficial species as well.

5. Conclusion

In this current study we investigated the effect of different cropping systems and years on the resulting population dynamics of beneficial and detrimental aerial arthropods. Crop rotations, no-tillage and residue retention involved in CA systems, increased biological control of pests through breaking their life cycles and through predation by natural enemies. Crop rotations play an important role in the attraction of a diverse arthropod population while reduced tillage mainly preserves the present arthropods which is adapted to periodic disturbance of the habitat. Tillage disturbs the habitats for some arthropods by burying crop residues and disrupting soil structure. This led on the other hand to more diverse arthropod communities hence no dominance of particular species under CA systems and keeping the communities in a diverse equilibrium.

We confirmed that CA systems usually result in richer arthropod communities. Rotations also break life cycles of both beneficial and detrimental species hence maintain a balance in the composition of the communities. The burning of cotton as advised by the extension services may not be necessary in CA systems because pest build-up is regulated by the increased biological and cultural control. We did not experience any significant increase of a pest under CA when cotton residues were retained on the soil surface. However, the pest dynamics on this trial should be revisited as it is still ongoing. To maintain as much as possible high fibrous carbon residues, we recommend keeping them on the soil surface in rotational systems with maize as opposed to exporting them outside of the field. This will enhance organic carbon in the soil when they decompose (although at a slower rate than when they are buried) and improve soil life of ground feeding organisms as well as provide shelter and habitat for predators. However, residues may be limited by their trade-off for other uses e.g., feeding livestock as well as by the need for extra labour to import them into the field, if they are not available, especially under smallholder farming set-ups. For cotton farmers being constrained by financial resources, effective and diverse rotations under CA might reduce the need to invest in expensive pesticides which are also a risk to human health and the environment. Diverse CA systems were able to keep the beneficial and detrimental organisms in equilibrium which is one of the goals of successful IPM.

Author contributions

CT designed and initiated the experiment and supervised data collection. RM and MS managed the experiment and collected the data. BM and NM analysed the data. BM, TM, NM, DM, and CT wrote the manuscript. All authors read and approved the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ethical approval

This article does not contain any studies with human participants or animals carried out by any of the authors.

Informed consent

Informed consent was obtained from all individual participants included in the study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocontrol.2020.104312.

References

Ajayi, O.C., Akinnifesi, F.K., Sileshi, G., 2011. Human health and occupational exposure to pesticides among smallholder farmers in cotton zones of Cote d'Ivoire. Health (N. Y.) 03, 631–637. https://doi.org/10.4236/health.2011.310107.

Aktar, M.W., Sengupta, D., Chowdhury, A., 2009. Impact of pesticides use in agriculture: their benefits and hazards. Interdiscip. Toxicol. 2, 1–12. https://doi.org/10.2478/v10102-009-0001-7.

Amera, T., Mensah, R.K., Belay, A., 2017. Integrated pest management in a cotton-growing area in the Southern Rift Valley region of Ethiopia: development and

application of a supplementary food spray product to manage pests and beneficial insects. Int. J. Pest Manage. 63, 185–204.
Bates, D., Maechler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67, 1–48.
Baudron, F., Zaman-Allah, M.A., Chaipa, I., Chari, N., Chinwada, P., 2019. Understanding the factors influencing fall armyworm (Spodoptera frugiperda J.E. Smith) damage in African smallholder maize fields and quantifying its impact on yield. A case study in Eastern Zimbabwe. Crop Prot. 120, 141–150. https://doi.org/10.1016/j.cropro.2019.01.028.
Bottrell, D.R., 1981. Integrated pest management. United States Government Printing Office, Washington DC.
Boyd, M.L., Phipps, B.J., Wrather, J.A., 2004. Cotton pests: scouting and management (Technical No. IPM1025), Integrated pest management. MU Extension, University of Missouri-Columbia.
Brainard, D.C., Bryant, A., Noyes, D.C., Haramoto, E.R., Szendrei, Z., 2016. Evaluating pest-regulating services under conservation agriculture: A case study in snap beans. Agric. Ecosyst. Environ. 235, 142–154.
Bretz, F., Hothorn, T., Westfall, P., 2016. Multiple comparisons using R, Illustrated. ed. CRC Press.
Brust, G.E., King, L.R., 1994. Effects of crop rotation and reduced chemical inputs on pests and predators in maize agroecosystems. Agric. Ecosyst. Environ. 48, 77–89.
Butler, D., Cullis, B., Gilmour, A., Gogel, B., 2009. ASReml-R reference manual: mixed models for S Language environments. Queensland Government, Department of Primary Industries and Fisheries, Brisbane, Australia.
Chimweta, M., Nyakudya, I.W., Jimu, L., Bray Mashingaidze, A., 2019. Fall armyworm [Spodoptera frugiperda (J.E. Smith)] damage in maize: management options for flood-recession cropping smallholder farmers. Int. J. Pest Manage. 1–13. https://doi.org/10.1080/09670874.2019.1577514.
Chitah, W.K., 2016. Cotton and its by-products in Zambia (Background No. 1617K). United Nations Development Account, Switzerland.
DeBach, P., Rosen, D., 1991. Biological control by natural enemies, 2nd ed. Cambridge University Press, Cambridge.
Dent, D. (Ed.), 1995. Integrated Pest Management. Springer Netherlands, The Netherlands.
Ehler, L.E., 2006. Integrated pest management (IPM): definition, historical development and implementation, and the other IPM. Pest Manag. Sci. 62, 787–789.
Eo, J., Kim, M., Ju Oh, Y., Park, S., 2017. Abiotic effects on the distributions of major insect species in agricultural fields. Entomol. Res. 47, 160–166.
FAO, 2012. Conservation agriculture.www.fao.org/reliefoperations (accessed 17 August, 2013).
Flint, M.L., Dreistadt, S.H., 1998. Natural enemies handbook: the illustrated guide to biological pest control. University of California, California, USA.
Foti, R., Chikuvire, T.J., 2005. Farm level pesticide use and productivity in smallholder cotton production in Zimbabwe: The case of Gokwe Communal Area Farmers. J. Sustain. Dev. Afr. 7.
Geiger, F., Bengtsson, J., Berendse, F., Weisser, W.W., Emmerson, M., Morales, M.B., Ceryngier, P., Liira, J., Tscharntke, T., Winqvist, C., Eggers, S., Bommarco, R., Pärt, T., Bretagnolle, V., Plantegenest, M., Clement, L.W., Dennis, C., Palmer, C., Oñate, J.J., Guerrero, I., Hawro, V., Aavik, T., Thies, C., Flohre, A., Hänke, S., Fischer, C., Goedhart, P.W., Inchausti, P., 2010. Persistent negative effects of pesticides on biodiversity and biological control potential on European farmland. Basic Appl. Ecol. 11, 97–105. https://doi.org/10.1016/j.baae.2009.12.001.
Harrison, R.D., Thierfelder, C., Baudron, F., Chinwada, P., Midega, C., Schaffner, U., van den Berg, J., 2019. Agro-ecological options for fall armyworm (Spodoptera frugiperda JE Smith) management: providing low-cost, smallholder friendly solutions to an invasive pest. J. Environ. Manage. 243, 318–330. https://doi.org/10.1016/j.jenvman.2019.05.011.
Hill, M.O., Gauch, H.G., 1980. Detrended correspondence analysis: an improved ordination technique. Vegetatio 42, 47–58. https://doi.org/10.1007/BF00048870.
Hobbs, P.R., Sayre, K., Gupta, R., 2008. The role of conservation agriculture in sustainable agriculture. Philos. Trans. R. Soc. B Biol. Sci. 363, 543–555. https://doi.org/10.1098/rstb.2007.2169.
Hoodle, M.S., Van Driesche, R.G., 1998. Biology and use of the whitefly parasitoid Encarsia formosa. Annu. Rev. Entomol. 43, 645–669.
Hruska, A.J., Gould, F., 1997. Fall Armyworm (Lepidoptera: Noctuidae) and Diatraea lineolata (Lepidoptera: Pyralidae): impact of larval population level and temporal occurrence on maize yield in nicaragua. J. Econ. Entomol. 90, 611–622. https://doi.org/10.1093/jee/90.2.611.
Jaipal, S., Singh, S., Yadav, A., Malik, R.K., Hobbs, P.R., 2002. Species diversity and population density of macro-fauna of rice–wheat cropping habitat in semi-arid subtropical northwest India in relation to modified tillage practices of wheat sowing, in: Herbicide-Resistance Management and Zero-Tillage in the Rice–Wheat Cropping System. Proc. Int. Workshop, Hissar, India, pp. 4–6.
Johan, A., 2017. Conceptual framework for integrated pest management. Trends Plant Sci.
Karuppaiah, V., Sujayanad, G.K., 2012. Impact of climate change on population dynamics of insect pests. World J. Agric. Sci. 8, 240–246.
Kendall, D.A., Chinn, N.E., Glen, D.M., Wiltshire, C.W., Winstone, L., Tidboald, C., 1995. Effects of soil management on cereal pests and their natural enemies, in: Glen, D.M., Greaves, M.P., Anderson, H.H. (Eds.), Ecology and Integrated Farming Systems. John Wiley and Sons Ltd, p. 83.
Ketipearachchi, Y., 2005. Predominant natural enemies of insect pests in agroecosystems at Aralaganwila in the North Central Province of Sri Lanka. SAARC J. Agric. 3, 263–276.
Kladivko, E.J., 2001. Tillage systems and soil ecology. XVth ISTRO Conf. Tillage Threshold 21st Century Look. Ahead 61, 61–76. https://doi.org/10.1016/S0167-1987(01)00179-9.
Kranthi, K.R., Jadhav, D.R., Kranthi, S., Wanjari, R.R., Ali, S.S., Russell, D.A., 2002. Insecticide resistance in five major insect pests of cotton in India. Crop Prot. 21, 449–460. https://doi.org/10.1016/S0261-2194(01)00131-4.
Lenth, R., 2019. emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.3.4. https://CRAN.R-project.org/package=emmeans.
Lepš, J., Šmilauer, P., 2014. Multivariate analysis of ecological data using CANOCO 5, 2nd ed. Cambridge University Press, Cambridge, UK.
M.H. Mahesh Effect of abiotic factors on soil meso- and macro-fauna in organic farming systems (MSc Agriculture) 2015 University of Agricultural Sciences Bengaluru.
Mashavakure, N., Mashingaidze, A.B., Musundire, R., Nhamo, N., Gandiwa, E., Thierfelder, C., Muposhi, V.K., 2019a. Soil dwelling beetle community response to tillage, fertilizer and weeding intensity in a sub-humid environment in Zimbabwe. Appl. Soil Ecol. 135, 120–128. https://doi.org/10.1016/j.apsoil.2018.12.001.
Mashavakure, N., Mashingaidze, A.B., Musundire, R., Nhamo, N., Gandiwa, E., Thierfelder, C., Muposhi, V.K., 2019b. Spider community shift in response to farming practices in a sub-humid agroecosystem of southern Africa. Agric. Ecosyst. Environ. 272, 237–245. https://doi.org/10.1016/j.agee.2018.11.020.
Maxmen, A., 2013. Crop pests: Under attack. Nature 501, S15.
McGavin, G., 2007. Expedition Field Techniques: Insects and Other Terrestrial Arthropods. Geography Outdoors, London, UK.
Mutema, M., Mafongoya, P.L., Nyagumbo, I., Chikukura, L., 2013. Effects of crop residue and reduced tillage on macro fauna abundance. J. Organ. Syst. 1.
Muthaiyan, M., 2009. Principles and practices of plant quarantine.
Ngowi, A.V.F., Mbise, T.J., Ijani, A.S.M., London, L., Ajayi, O.C., 2007. Smallholder vegetable farmers in Northern Tanzania: pesticides use practices, perceptions, cost and health effects. Crop Prot. 26, 1617–1624. https://doi.org/10.1016/j.cropro.2007.01.008.
Odendo, M., Ouma, J., Wachira, S., Wanyama, J., 2003. Economic assessment of maize yield loss due to stem borer in major maize agro-ecological zones of Kenya, in: African Crop Science Conference Proceedings. African Crop Science Society, Uganda, pp. 683–687.
Oksanen, J., Blanchet, F.G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P. R., O'Hara, R.B., Simpson, G.L., Solymos, P., Henry, M., Stevens, H., Szoecs, E., Wagner, H., 2019. vegan: Community Ecology Package. R package version 2.5-5. https://CRAN.R-project.org/package=vegan.
Pearson, E.O., 1958. The insect pests of cotton in tropical Africa. Empire Cotton Growing Corporation and Commonwealth Institute of Entomology, London.
R Core Team, 2019. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.
Rabary, B., Naudin, K., Letourmy, P., Hassani, I., Randriamanantsoa, Michellon, R., Rafarasoa, L., Ratnadass, A., 2011. White grubs, Scarabaeidae larvae (Insecta, Coleoptera) control by plants in Conservation Agriculture: effects on macrofauna diversity, in: 5 Th World Congress of Conservation Agriculture. Presented at the 3rd Farming Systems Design Conference, Brisbane, Australia.
Rämert, B., Lennartsson, M., Davies, G., 2003. The use of mixed species cropping to manage pests and diseases – theory and practice, in: Powell, J.M. (Ed.), UK Organic Research 2002: Proceedings of the COR Conference, 26- 28th March 2002. Aberystwyth, pp. 207–210.
Rourke, K., 2017. Attracting beneficial insects to your farm: a comparison of habitat modification strategies (Master of Science). The University of San Francisco.
Rusch, A., Valantin-Morison, M., Sarthou, J.-P., Roger-Estrade, J., 2010. Biological control of insect pests in agroecosystems: Effects of crop management, farming systems, and seminatural habitats at the landscape scale: a review. Adv. Agron. 109, 219.
Shannon, C.E., Weiner, J., 1963. The Mathematical Theory of Communication. University of Illinois Press, Urbana.
Sinclair, A.R.E., Mduma, S., Brashares, J.S., 2003. Patterns of predation in a diverse predator–prey system. Nature 425, 288–290. https://doi.org/10.1038/nature01934.
Snyder, W.E., 2019. Give predators a complement: conserving natural enemy biodiversity to improve biocontrol. Biol. Control 135, 73–82.
Stamps, W.T., Linit, M.J., 1997. Plant diversity and arthropod communities: implications for temperate agroforestry. Agrofor. Syst. 39, 73. https://doi.org/10.1023/A:1005972025089.
Stewart, S.D., Jackson, T., Cotton, B., 2003. Insect management in reduced tillage systems, in: 2003 Beltwide Cotton Conference. National Cotton Council, Nashville, pp. 110–112.
ter Braak, C.J.F., 1986. Canonical correspondence analysis: a new eigenvector technique for multivariate direct gradient analysis. Ecology 67, 1167–1179. https://doi.org/10.2307/1938672.
Ter Braak, C.J.F., Šmilauer, P., 2002. CANOCO reference manual and CanoDraw for Windows user's guide: Software for Canonical Community Ordination (version 4.5). Microcomputer Power, Ithaca, New York.
Thierfelder, C., Rusinamhodzi, L., Ngwira, A.R., Mupangwa, W., Nyagumbo, I., Kassie, G.T., Cairns, J.E., 2014. Conservation agriculture in Southern Africa: advances in knowledge. Renew. Agric. Food Syst. 1–21. https://doi.org/10.1017/S1742170513000550.
Thierfelder, C., Wall, P.C., 2010. Rotations in conservation agriculture systems of Zambia: effects on soil quality and water relations. Exp. Agric. 46, 309–325.
Thierfelder, C., Wall, P.C., 2009. Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. Soil Tillage Res. 105, 217–225.
Urbaneja-Bernat, P., Pérez-Rodríguez, J., Krüger, K., Catalán, J., Rizza, R., Hernández-Suárez, E., Urbaneja, A., Tena, A., 2019. Host range testing of Tamarixia dryi (Hymenoptera: Eulophidae) sourced from South Africa for classical biological control of Trioza erytreae (Hemiptera: Psyllidae) in Europe. Biol. Control 135, 110–116.

https://doi.org/10.1016/j.biocontrol.2019.04.018.
Walker, P.T., 1983. Crop losses: The need to quantify the effects of pests, diseases and weeds on agricultural production. Agric. Ecosyst. Environ. 9, 119–158. https://doi.org/10.1016/0167-8809(83)90038-5.
Wallner, W.E., 2003. Factors affecting insect population dynamics: differences between outbreak and non-outbreak species. Annu. Rev. Entomol. 32, 317–340.
Wickham, H., 2016. ggplot2: Elegant graphics for data analysis. Springer-Verlag, New York, USA.
Wild, S., 2017. Invasive pest hits Africa - as hungry caterpillar eats its way through 12 countries, researchers begin to fight back. Nature 543, 13–14.
Wood, T.G., Cowie, R.H., 1988. Assessment of On-Farm losses in cereals in Africa due to soil insects. Int. J. Trop. Insect Sci. 9, 709–716.
WRB, 1998. World reference base on soils. FAO-ISRIC, Rome, Italy.
Wu, J.G., Luan, T.G., Lan, C.Y., Lo, W.H., Chan, G.Y.S., 2007. Efficacy evaluation of low-concentration of ozonated water in removal of residual diazinon, parathion, methyl-parathion and cypermethrin on vegetable. J. Food Eng. 79, 803–809. https://doi.org/10.1016/j.jfoodeng.2006.02.044.
Zukowski, J., Su, N., 2017. Survival of termites (Isoptera) exposed to various levels of relative humidity (RH) and water availability, and their RH preferences. Fla. Entomol. 100, 532–538.